

SEISMIC RETROFITTING OF UNREINFORCED MASONRY BUILDINGS IN ITALY



2006 NZSEE
Conference

S. Frumento, S. Giovinazzi, S. Lagomarsino, S. Podestà

Department of Structural and Geotechnical Engineering, University of Genoa, Italy

ABSTRACT: The Italian heritage building stock is dominated by unreinforced masonry buildings widespread on the whole territory with rammed earth buildings peculiar of some regions. A major effort is given to strengthen or retrofit these buildings in order to improve their safety under seismic loading as well as to preserve them as memory of the ancient art of builders and as constitutive elements of the anthrop-environment. This paper describes traditional seismic retrofit interventions adopted in Italy. These retrofitting interventions, revised according to the modern technologies, derived from historical concept of aseismic devices (i.e. metallic tie-rods, circumferential tie-rods, buttresses, “diatoni”, wall connections, partial reconstruction of walls) suggested to the builders’ crafts by observation of earthquake damage and imposed by the past technical rules. A good degree of confidence on the feasibility, compatibility and effectiveness of these techniques for URM buildings is guaranteed after having been extensively tested during the centuries. Recently, technical national code-guidelines for the seismic retrofit of existing URM masonry buildings have been prepared with the specific purpose to help practitioner engineers to implement these solutions.

1 INTRODUCTION

Unreinforced masonry buildings are characterized by an intrinsic vulnerability to the seismic action being only gravity load designed. Moreover, especially in historical centers, they often results from non homogeneous constructive phases due to extensions occurred in the past by merging parts or superimposing new ones. The inadequate connection of parts through excessively slender elements can result into overturning mechanisms when subjected to seismic lateral loading.

Rules of thumbs were established in the past in order to prevent such mechanisms, by implementing connections between orthogonal walls, adequately stiffened metallic tie-rods, circumferential tie-rods, buttresses and “diatoni”. However, being the earthquake a long return period (low probability) event, these rules did never become part of the constructive practice and were sporadically applied, usually for a short period immediately following the earthquake event and often in the forms of quick strengthening intervention during the post-earthquake survey and repairing phases.

The severe damages suffered by repaired and strengthened URM buildings after recent earthquakes in Italy, have proved the inadequacy of the retrofitting strategies and techniques adopted in the last thirty years. Examples of inadequate interventions have been given by the introduction of additional reinforced concrete elements in the form of rigid diaphragm, r.c. ring beams, columns inserted within the depth of the walls without specific attention to the effects of an increased level of mass and stiffness. Unexpected local or global failure mechanisms due to the enforced deformation incompatibilities with the original structures could result.

These issues opened a wide cultural debate, exacerbated by a strong public opinion reaction after the Molise Earthquake event in 2002, where the partial collapse of a primary public school caused the

decease of twenty seven children. As a result, a new seismic hazard zonation was approved along with the development of a new seismic code (OPCM 3431/05), issued by the Italian Civil Protection Department. In particular, a special Annex 11E has been included specifically focussed to the description of alternative feasible retrofit and strengthening techniques for Unreinforced Masonry Buildings. The different proposed solutions have been subdivided based on their targeted performance objective, while highlighting limits and positive features of each solution also depending of the masonry typology. In this paper, an overview of the alternative retrofitting solutions presented in the Annex 11E is given, with the intent to create a sound basis for discussion on their possible compatibility with the peculiarities of URM buildings in NZ. Explicatory figures from construction practice or design handbooks (Blasi et al. 1999, ERTAG 1986, Regione Campania 2004, Regione Marche 2000) are also given for each methodology.

2 RETROFIT INTERVENTIONS AIMING TO IMPROVE STRUCTURAL CONNECTIONS

The aims of these interventions are: a) to favour a monolithic three-dimensional behaviour of the structure, against the horizontal seismic loads, by means of wall-to-wall and floor-to-wall connections, b) to contain the lateral loads from vaults and roof.

The three-dimensional behaviour represents a minimum requirement in order to apply analytical methods for the seismic analysis of the whole building. As a matter of fact these methods assume the wall behaviour is dominated by in plane action, being the out-of-plane mechanisms constrained.

To reach these goal viable solutions proposed by Annex 11E are: 1) metallic or different material tie-rods; 2) external circumferential tie-rods; 3) local connections; 4) ring beams. A brief description of advantages and limits of each solution, along with implementation issues, is given below.

2.1 Metallic or different material tie-rods

Metallic tie-rods should be located at the floor level along the two principal directions of the structure (Fig. 1a), and anchored by means of rosehead washers bearing plates. They favour the development of a three-dimensional behaviour of the structure providing a valuable connection between orthogonal walls and supplying restraints against the out of plan mechanisms of the walls. In addition they can significantly improve the in plane behaviour of walls with openings, by developing a strut and tie mechanism in the spandrels below and above the opening.

For an efficient implementation, tie-rods must have a suitable stiffness (big diameter and limited length bars being preferred); the pre-stressed force should be controlled within appropriate values in order to avoid local damages. When adopting rosehead washers bearing anchorage, inclined bolts (Fig. 1b) should be preferred to actual plates as they involve a wider portion of the masonry wall. Anchorage plates (Fig. 1c) have to be preferred when dealing with low-quality masonry (i.e. stone-masonry made of little elements) which need to be locally reinforced. It is not recommended to locate the anchorage into the wall section, particularly dealing whit disconnected rubble filled stone masonry walls.

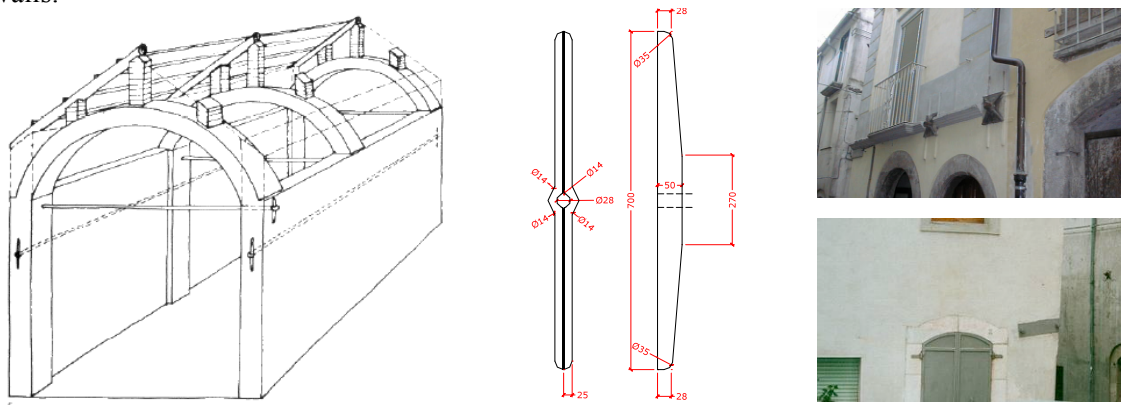


Figure 1. Improvement of structural connection: a) Metallic tie-rods along the two main direction of the structure, b) details of rosehead washer bearing bolt, c) examples of rosehead washer bearing bearing plate

2.2 External circumferential tie-rods

External circumferential tie-rods can be made of metallic elements (Fig. 2a), FRP (fibre reinforced polymers) or other composites (Fig. 2b). They further enhance the three-dimensional behaviour of the structure providing a effective connection between orthogonal walls. This retrofit intervention is effective for buildings with limited wall length. Concentration of tensile stressed in the building corners should be avoided by means of additional repartition plates or by smoothing the corners when FRP strips are adopted.



Figure 2. External circumferential tie-rods: a) metallic elements, b) FRP or other composites (Blasi et al. 1999)

2.3 Local connections: disconnecting and reconnecting adjacent units, installation of steel ties, installation of metallic or other material transversal connections.

Alternative technique to improve local connections in stone or masonry buildings can be achieved by disconnecting and reconnecting adjacent units or elements (Fig. 3a), by the installation of steel ties (Fig. 3b) or by the installation into drilled holes of transversal elements made of conglomerate, or reinforced with metallic or FRP bars (Fig. 3c).

Local connections aim to improve wall to wall connection when existing wall joints are deteriorated either due to seismic or non seismic-related damages or are intrinsically of poor quality. However, they are effective in enhancing the building three-dimensional behaviour only when dealing with good quality masonry. For poor quality masonry, a meaningful improvement of the global behaviour is not guaranteed by this solution and the adoption of ties has to be preferred.

The use of deep drilling and reinforcing has to be considered only when no other option can be adopted and avoided for rubble filled stone masonry walls. Attention should be given to the durability of the elements adopted as transverse tie (e.g. stainless steel, composite materials, fibre reinforced polymers or others materials) as well as to the chemical compatibility of the injected mortar.

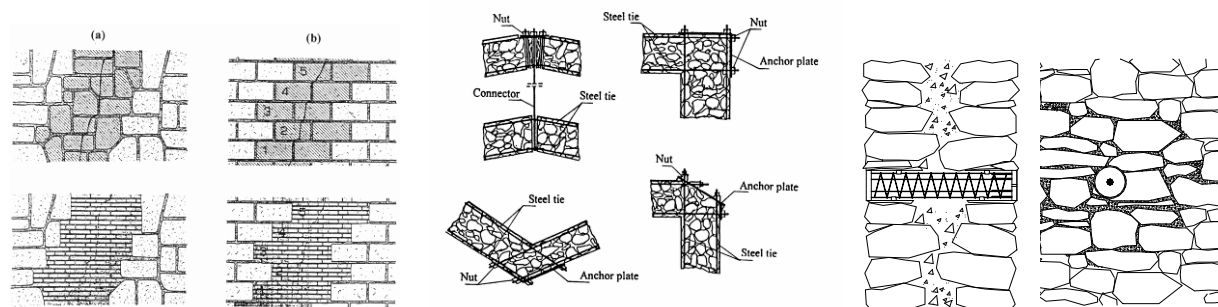


Figure 3. Local connections: a) disconnecting and reconnecting adjacent units, b) installation of steel ties, c) reinforcing steel bars grouted into drilled holes.

2.4 Ring beams

Ring beams represent an effective solution to improve the wall to wall connections (in the upper part of the building where the masonry wall is characterized by a limited cohesion because of a limited compressive level) and to improve the wall to roof connection. Different techniques and material can be employed, ranging from reinforced masonry to steel or reinforced concrete ring beams.

Reinforced masonry ring beams allow achieving a high level of preservation and compatibility with the characteristics of the existing masonry walls. A good quality masonry material has to be used along the whole wall thickness. The most natural solution is the use of bricks. Steel reinforcement is located in the masonry ring beam and bond is provided via cement mortar. The connection to the existing wall connection can be obtained, when dealing with good quality mortar, through the post-installation of grouted reinforcing steel bars, only dealing with good quality masonry. For poor quality masonry, a local strengthening of the upper part of the wall is needed and the connection is guaranteed by simple friction.

Steel ring beams (Fig. 4) represent a valid alternative to the previously proposed solution, thanks to their lightness, limited invasiveness and the fact that they allow proper connections with the timber elements of the roof (possibly limiting their horizontal loads). They can be realized employing a steel truss made of steel angle or plates or placing steel plates on the inner and outer sides of the wall, connected through transverse threaded bars or rods. A satisfactory connection to the wall can be achieved in either case without the use of post-installed bars. A local strengthening of the masonry wall is still required when dealing with poor quality masonry.

An effective variation to the previous proposed solution, not yet included in the Annex, is to locate the steel ring-beam on both sides of rather than at the top of the wall. In this way the intervention can be implemented without the need to remove the existing roof, to demolish the upper part of the wall, or to increase the roof level. Moreover, in this configuration the masonry wall is more stable with respect to the upper part, thanks to the contribution of the vertical load from the roof. The lateral ring beam can be realized by a double steel truss structure (both on the inner and outer side of the wall) welded together directly on site in order to minimize issues related to geometrical irregularities. The connection between the inner and outer lateral steel ring beams will be guaranteed through drilled and grouted bars/rods.

Reinforced concrete ring beams can be realized only if limited in height, in order to avoid excessive increase in weight and stiffness as well as in tangential stresses between the ring beam and the wall, which could lead to sliding of the ring beam and desegregation of the masonry wall. Because of the difference in stiffness between masonry and reinforced concrete element, a local strengthening of the upper part of the wall can be in any case required. The connection to the wall can be improved by using post-installed grouted bars/rods.

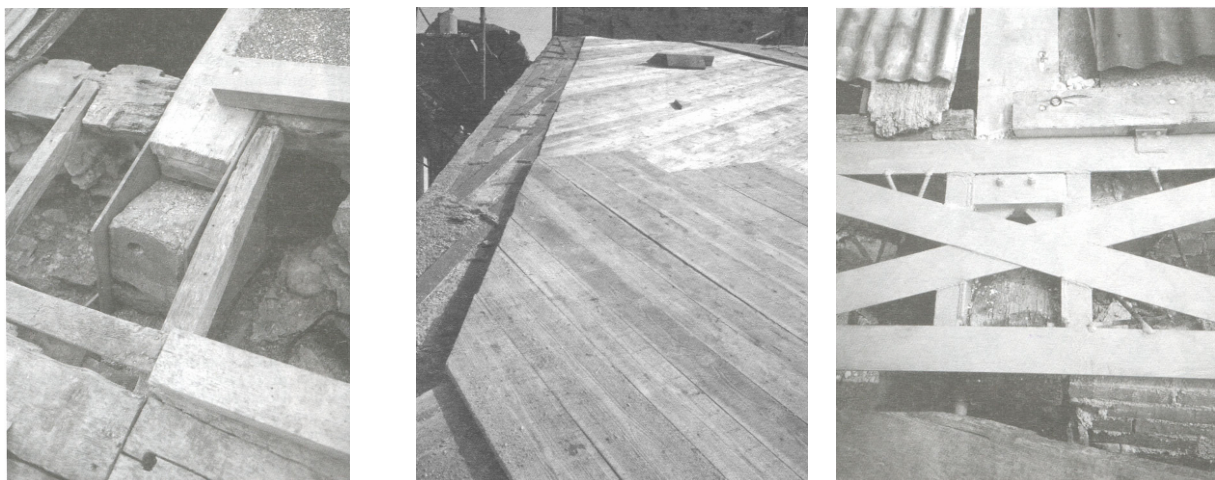


Figure 4: Steel ring beam: a) connection between the wood roof element and the walls; b,c) partial strengthening of the plywood panel diaphragm and its connection with the steel ring beams (Regione Marche 2000).

An effective connection between the horizontal slab and the ring beam has to be obtained in order to avoid sliding of the wooden slab beams and the consequent collapse of the slab. The connection between ring-beam and wall allows, moreover, for a better distribution of the horizontal seismic load and provides a restrain against overturning mechanisms of the wall. Local connections can be realized through drilled holes, provided excessive disturbance to the wall is avoided. The insertion of ring beams in the wall thickness has to be avoided at low floor levels. In fact, they can cause negative effects on the load distribution along the wall.

3 RETROFIT INTERVENTIONS AIMING TO REDUCE THE FLOOR SLABS DEFORMABILITY

In order to guarantee an appropriate seismic response of the building, horizontal slabs are expected to transfer horizontal loads to the walls placed in the same directions of the seismic actions and to represent a restrain against the overturning of the walls, under horizontal orthogonal loads.

3.1 Timber slab stiffening

An increase in stiffness of the timber slab can be achieved by nailing on the extrados of the existing plywood panel diaphragm a second panel, arranged with an orthogonal or inclined course (Fig. 5a). Particular care should be given to the connection with the lateral wall. In addition, or as an alternative choice, steel or composite materials strips can be fixed on the existing plywood panel diaphragms according to a crossing course (Fig. 5b). An analogous result can be achieved adopting steel tie bracing (Fig. 5c).



Figure 5. Timber slab extrados stiffening: a) addition of a new plywood panel diaphragm over an existing one, b) FRP strips, c) steel strips inside the slabs.

3.2 Timber slab flexural strengthening

Direct strengthening of the timber beams can be obtained increasing the structural section by connecting additional elements in the compression zone. When a static strengthening of the slab is needed due to flexural loading, both the in-plane and out-of-plan upgrading can be achieved, wood-to-wood techniques can still be effectively implemented, provided the new added plywood panel is set longitudinally when respect to the existing one. As typical of such solutions, an effective connection between the two has to be guaranteed by means of timber or other material connectors. An increase of stiffness of the new plywood panel diaphragm can be obtained with a further finishing plywood d panel. Punctual connections can be employed in order to improve non-adequate wall-to-plywood panel diaphragm connections (Fig. 6).

An alternative of wood-to-wood techniques has typically comprised of cast-in-situ of lightweight concrete topping (Fig. 6). Care has to be taken considering this solution with regard to the consequent increase of mass and the different distribution of the seismic loading.

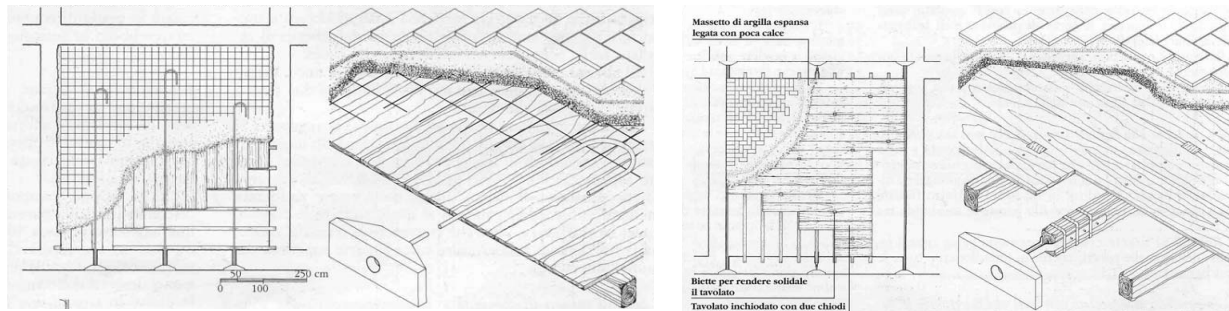


Figure 6. Timber slab static strengthening: casting over of lightened reinforce concrete topping overlays and punctual wall-to-plywood panel diaphragm connections (Blasi et al. 1999).

4 RETROFIT INTERVENTIONS AIMING TO INCREASE THE STRENGTH OF PIER WALLS

Poor quality masonry pier walls can be subjected to disaggregating collapse mechanisms of the outer side of the wall, due to widespread cracks. The installation of transversal connections within rubble filled walls is a primary need, as the analytical methods for the local or global seismic analysis assume a monolithic transversal behaviour of the wall. Anyway these interventions alone are insufficient to favour the three-dimensional behaviour of the building and to improve the whole structural integrity.

The most proper intervention has to be chosen on the basis of the building typology and quality, among the possible alternatives herein presented, the most proper intervention has to be chosen on the basis of the building typology and quality. Materials with the highest compatibility both from the physical-chemical and mechanical point of view have to be employed. Non masonry-based elements, and in particular reinforced concrete elements, have to be employed with caution.

In order to restore the wall continuity along the cracks and in regions of high deterioration, adjacent units or elements can be disconnected and reconnected (Fig. 3a). The same technique can be employed to reduce or to infill small or large openings. Materials similar to the original ones for shape, dimension, stiffness and strength have to be used. The newly introduced elements have to be linked to the original ones through proper connections in-plane and perpendicularly to the wall, in order to achieve a homogeneous and monolithic behaviour of the wall.

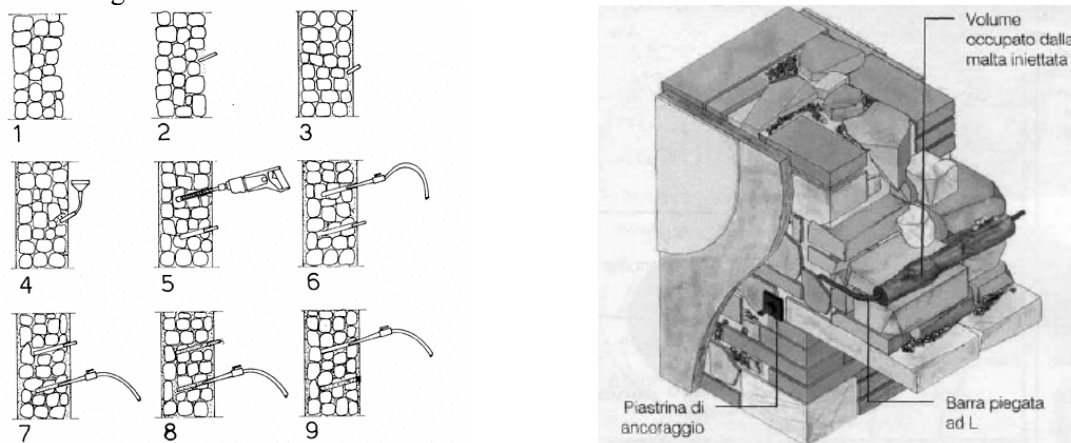


Figure 7. Increase the pier strength: a) grout injections, b) reinforced injections (Blasi et al. 1999).

Grout injections (Fig. 7a) can be employed to improve the mechanical characteristics of the wall by increasing the continuity of the masonry and hence its strength. This intervention can not be applied when the masonry typologies cannot be properly injected due to the low percentage of voids. Particular care has also to be taken when choosing the injection pressure and the type of mortar/grout to be injected in order to avoid chemical and physical incompatibility with the wall.

Steel reinforcing or FRP bars can be grouted or cemented into drilled holes (Fig. 3c, Fig. 7b) in order to increase the pier strength and prevent instability phenomena (Lagomarsino et al. 2001). This technique can be used also on poor quality masonry, since it does not induce damages during the execution. It is particularly suitable for rubble filled walls as it improves the effective transversal connection between the inner and the outer withes. In the case of degraded withes, it is advisable to firstly employ strengthening techniques such as grout injections or restoring the mortar beds.

Restoring the mortar beds, when penetrating the depth of the wall from both side, can lead to significant improvements of the masonry mechanical parameters, particularly for low thickness masonry wall. For walls characterized by medium and high thickness and by non-suitably connected withes, this intervention could be insufficient to guarantee an actual increase in strength and should thus be suggested only in combination with other interventions. Particular care is required in the selection of the mortar. The possible installation of bars, metal or FRP strips when restoring the mortar beds, can further increase the intervention efficiency (Fig. 8a).

If the portion of the masonry wall requiring a retrofit intervention is limited, small diameter transversal bars, bolted through washer on both the sides of the wall can be adopted as a valid alternative (Fig. 8b) to increase the pier strength. A small pre-tensioning can be applied in presence of detached withes and to contain out-of-plane local deformations. This technique can be used when dealing with regular texture masonry typologies, squared stones, blocks or bricks. The adoption of ties widespread along the three orthogonal directions, but particularly in the transverse direction, can increase the monolithic and mechanic behaviour of the wall, increasing the shear strength and the in-plane and out-of-plane flexural strength.



Figure 8. Strengthening solution for pier walls: a) restoring of mortar joints and installation of steel bars, b) transversal bars bolted through washer.

In order to improve the connection of the wall and to increase the mechanical properties of the wall, traditional jacketing techniques can be adopted. A reinforcing mesh (6 to 8mm diameter) can be placed on both faces of a wall and connected by transversal steel ties. Cover is provided by a cement-mortar-based layer. It is not advisable to adopt this technique for the whole building due to the major increase in stiffness and mass as well as for preservation and functional reasons. This technique is only effective if the wall jacketing is realized on both side of the wall and proper transverse connections are adopted (e.g. post-installed reinforcing steel bars). A mesh consisting of FRP strips can also be used as an alternative to the steel mesh when dealing with regular masonry typologies (Fig. 9c). The efficacy of this alternative technique is increased when the mesh is positioned on both sides of the wall.

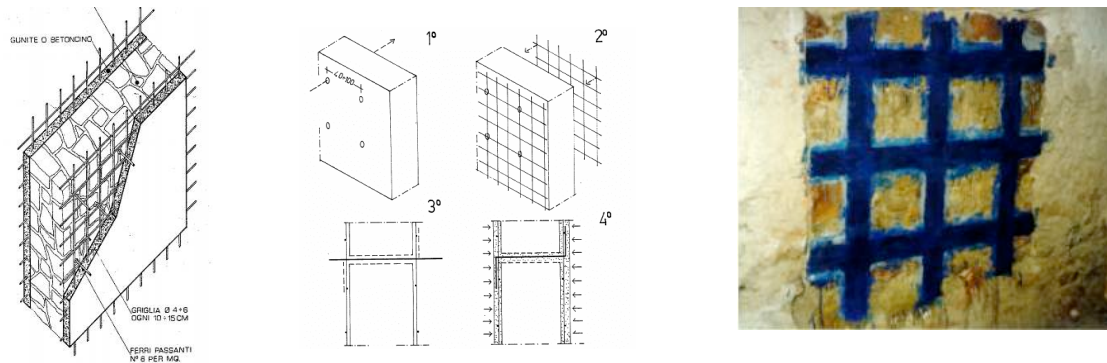


Figure 9. Increase the shear strength: a) b) Wall and pier jacketing, c) Wall and pier jacketing with FRP strips.

Vertical post tensioned tendons can be efficiently used provided that the masonry walls are able to sustain the increased level of compression loads at local and global level. Particular attention should be given to the tendon anchorage zones. Losses in the prestressing force, due to differential deformations in the masonry (e.g. due to creep and shrinkage) have to be taken into account.

5 CONCLUSION

The complexity of retrofit interventions on heritage or existing URM buildings is well-known. Nevertheless, the crucial need for simple, feasible and moderately-invasive upgrading interventions, along with design methodologies and guidelines has become a primary goal of seismic mitigation strategies. In this contribution, a discussion of technical recommendations recently released within the new Italian seismic design code-guidelines has been presented (Annex 11E). with the intent to create a sound basis for discussion on their possible compatibility with the peculiarities of URM buildings in NZ. Examples from construction practice or design handbooks have been also given for each proposed solution, highlighting limits and positive features depending of the masonry typology.

The identification of the most effective intervention requires a careful assessment of the seismic vulnerability and potential collapse mechanisms of the building due to constructive and technological deficiencies. Within a range of structurally efficient seismic retrofit upgrade options, considerations on cost and invasiveness will dictate the selection of the most appropriate solution, based on a case-by-case evaluation.

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